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REVIEW OF LANGLEY PROGRAMS CONCERNED

WITH ORIENTATION IN SPACE

By Warren Gillespie, Jr.

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ABSTRACT - For February 25-27, 1959 Meeting at Ames Research Center - Review of NASA Research Related to Control, Guidance and Navigation of Space Vehicles.

REVIEW OF LANGLEY PROGRAMS CONCERNED WITH ORIENTATION IN SPACE

Warren Gillespie, Jr.

The Langley research effort on attitude control for space vehicles was initiated in part by general studies of the problem. For example, the matching of satellite mission stabilization requirements with control system capabilities was investigated. Radiation-sensing systems employing active controls were indicated to be versatile and capable of early development. Control by passive methods should permit increased reliability. The gravitational method of orientation toward earth can be applied to satellites of small mass by use of an erectable structure technique.

Studies are underway on different sensors for provision of attitude reference, different types of controls and on system designs for specific applications. This leads to the desirability of some form of ground simulation. Work in this area is in progress.

This program is briefly outlined and will be discussed generally as follows:

1. Surveys and Comparisons
2. Requirements and Tradeoffs
3. Control Systems
4. Simulation Tests
5. Space Flight Experiments

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INTRODUCTION

The Langley research programs concerned with orientation in space will be broadly discussed under the five major areas shown on the first slide. These areas are: Surveys and Comparisons, Requirements and Tradeoffs, Control Systems, Simulation Tests, and Space Flight Experiments. While much of the current work in these areas is applicable to both satellite and deep space-probe vehicles, there is a somewhat greater emphasis on the former. The probable reason for this is perhaps the more immediate benefits that may be derived from satellite exploitation of space.

SURVEYS AND COMPARISONS

In the first category, the next slide lists two studies that have been completed.

The study of Attitude Control of Earth Satellite Vehicles took as an objective the matching of satellite mission stabilization requirements with control system capabilities. The probable missions in an advanced satellite program were considered under the following categories:

1. Space Environment
2. Astronomy and Astrophysics
3. Meteorology
4. Communications
5. Space Flight Technology

Information obtained through the Space Science Board of the National Academy of Sciences was very helpful in these considerations.

The possible stabilization methods were considered under these headings:

1. Spin stabilization
2. Gravitational-Centrifugal-Force Gradient Method
3. Earth horizon scan, area scan
4. Sun, Star-Tracking Methods
5. Other systems utilizing ionization or microphone devices, monitored inertial references and a combined horizon-scan and gravity system.

While the requirements in some cases could not be accurately defined it was seen that they ran the gamut. In many cases the pointing direction need only be known or the vehicle de-spun or slowed as in the case of an initially spinning vehicle. The additional time for data workup, however, may well warrant a more sophisticated control system be used. Most stringent is the pointing of a large telescope operating near its limit of resolution which for a 20-inch telescope would require a pointing accuracy of about 0.10 second of arc. This is made more difficult in the case of star-tracking by the stellar motions and by the aberration of light that will introduce continuous tracking maneuvers of about $\pm$ 5 seconds of arc per orbital revolution. Thus, very coarse to very fine control systems must be developed. This will require much detailed analysis and experimentation for accomplishment.

The currently-used, open-loop method of spin stabilization is well known. A somewhat different approach is illustrated by the next slide.

Here the spin axis has been oriented to be normal to the plane of the orbit. To maintain this relationship either an exactly polar or an exactly equatorial orbit is selected. A horizon sensor provides earth attitude reference, altitude information and triggers a weather or space eye for viewing toward or away from the center of the earth. Additional controls would be provided to maintain a desired spin rate against magnetic damping and other perturbations. The configuration need not be restricted to a cylinder as shown but could also be a high fineness ratio body rotating about its axis of greatest inertia.

The next slide shows two launching schemes for small erectable satellites stabilized by the gravitational method. Such an erection technique in the case of a vehicle with a nuclear power source could reduce the radiation hazard and weight of shielding required. On the left the vehicle is initially spinning at injection. It is permitted to spin for one-quarter or three-quarters of a revolution, depending upon the final orientation desired, and is then despun and erected. On the right, the launching vehicle performs a pitch-down maneuver as in the case of the Air Force satellite. This maneuver must be very precise to avoid tumbling and overworking of a damping control system. An error in pitching rate of 2 milliradians per second for a 500-mile orbit would initiate a game of "Sputnik Roulette" in which either the right or wrong orientation would eventually come up after damping of the rotation. For the method on the left, initial amplitudes of about 35 degrees should occur for all altitudes of injection. The altitude to which this gravity stabilization can be used depends upon the stabilizing moment that can be developed to overcome environmental disturbances. The moment, of course, weakens very quickly with increasing altitude. The next slide shows the effect of a slightly eccentric orbit of e = 0.005 on orientation with injection at 500 miles and pitching rate equal to the circular orbital rate at this altitude. The digital computer solution is shown for the first revolution with no damping. Additional computations show that the maximum error increases linearly with the orbit eccentricity and is not appreciably greater for succeeding revolutions around the earth. (Slide off please.)

Also considered were many interesting variations of earth-horizon and area scan methods which derive attitude reference from electromagnetic or cosmic rays. In particular, the horizon scan method using a thermistor bolometer operating in the far infrared is most feasible for continuous night and daytime operation, and in fact, two such scanning units are commercially available, with accuracy of attitude determination estimated to be close to 1 degree. Such scanner units are designed to work under conditions of varying altitude and intensity of radiation. For this type of stabilization, controls can be designed to handle any magnitude of perturbation anticipated at injection or later. Usable lifetime for the system should be at least several months. If better accuracy is required, a photoelectric-type sensing unit could be used to supplement the bolometer for full daylight viewing of the earth.

Tracking the sun is much easier, since there is essentially no distance variation and the sun can be considered as a point source of light. The sun can also be viewed continuously as shown by the next slide.

Circular orbits between 200 and 4300 miles altitude and corresponding inclinations between 83° and 26° can be selected for steady viewing. The method of attitude sensing used by the University of Colorado in a balloon flight appears very good with a maximum pointing accuracy of about 5 seconds achieved during the flight. The attitude sensing consists of two sets of coarse and fine sensors. Both sets use a light-diffusing disc but in addition the fine sensor has an objective focusing lens. The attitude signal is shown in the next slide. Both sets of sensors work simultaneously with the gain set higher for the fine sensors. A wide angle of capture is assured by the coarse sensors and fine control by the second set of sensors. This system, I believe, was proposed by McDonnell in the "Solarscope" proposal along with provision for third-axis control by star-tracking North and South-Ecliptic stars. (Slide off)

With regard to star-tracking, appropriate orbits can also be selected in most cases to permit continuous tracking. The acquisition of a particular star may be difficult since there are so many. A survey capability of a local region of the celestial sphere may be required with automatic programming and map-matching schemes used. Ground command control is highly desirable for a more flexible program with viewing at a ground station. Programs underway by the Air Force, notably the "Cat-Eye" television system using an RCA image orthican tube for visual presentation, a storage integrator to see a very faint objective and a third device for detecting a moving object, these programs seem applicable to the Astronomical mission.

Finally, in this first study, the momentum, torque and power of various angular maneuvers were calculated. These included maneuvers at injection, those of an intermittent or recurring nature and those of a steady nature. The initial transient maneuver was used as a basis for estimating weight and power required by flywheel control units for satellites ranging in size up to 3000 lb. for different stabilization methods. The spin and gravity systems with no damping were optimum on this basis. At 3000 lbs. the gravity method with active damping appeared slightly better than the horizon-scan method but in either case the control system weight appeared to be less than 50 lb. and power less than 100 watts.

Referring again to slide number two (may we have slide 2 again please), the second study was based on a relatively severe angular tracking maneuver of a satellite. A vehicle of 3000 lb. was assumed to be traveling in a 300-mile circular orbit. The angular maneuver consisted of tracking with zero error a point on the earth's surface during the time this point was directly visible. Jet control with hydrogen peroxide, flywheel control and a bar magnet control, interacting with the earth's magnetic field were the types considered. This latter magnetic control requires by far the most weight and is restricted in use by large variations of the magnetic field along certain orbits. By itself, the bar magnet does not warrant further consideration. As between the jet and flywheel controls, the jet would be preferred for a limited number of cycles. The cross-over point will depend on the severity of the maneuver and considerations such as the relative size of flywheel to vehicle and power source for the flywheel. A control unit for one axis of rotation can weigh less than 1 percent of the satellite weight.

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REQUIREMENTS AND TRADEOFFS

From these initial studies it is clear that a space orientation program should be broad enough to include considerations of trade-offs as between the control system and other systems of the space vehicle and including its launching vehicle as well as a continuing effort to match control system performance and reliability with mission requirements. Some investigation in this direction has taken place at Langley. In particular, we note a solar-power study was recently completed.

This showed the desirability of a liquid-vapor cycle using a solar-oriented collector for power levels of 4 kw or greater.

A large effort is presently underway at Langley on a 100-foot diameter spherical relay that is of course not oriented but has the problem of despinning prior to erection. Studies by others have shown that about 8 or 10 of these relays can be used in 1000 mile polar orbits to establish communications between the United States and Europe. The next slide shows a passive-type relay that is under preliminary study. The reflecting surface is a spherical segment of a very large sphere that as a complete sphere would not be practical to build. The problem is to optimize the satellite by minimizing communication power at the ground stations, number of satellites, size, weight and pointing accuracy of the orientation control system for an indefinite lifetime of operation. Either the gravity or horizon-scan stabilization method could be employed or both together. For some modes of scanning with a horizon system, the configuration will block the view. A suitable scanning mode must be selected to avoid this. An inflatable honeycomb structure of aluminum-mylar appears able to provide the necessary stiffness to maintain shape of this configuration.

In the next slide is shown an arrangement for a solar- and earth-oriented satellite that is under investigation. A parabolic solar-energy collector and internal power system are solar oriented. For a power system using a turbine it is desirable to point this unit toward the sun rather than the earth to minimize precessing the turbine axis by the control system. For an earth-oriented payload located near the rim of the collector, the view will at times be blocked by the collector. The vehicle can be rolled about the solar-direction at such times. An alternate arrangement is to use two earth-seeking units working as a pair to avoid blocking of the view. (Slide off please)

CONTROL SYSTEMS

Now let us take a closer look at control programs. As shown by the next slide on the left hand s~~l~~ide, (slide 12), the work covers different types of stabilization methods, attitude sensors, controls and system analysis and on the right side extends into simulation tests of attitude sensing units, controls and complete systems and lastly, space flight experiments using vertical rocket probes and satellites.

Considering first the work wherein the main approach is analytical, in the area of spin stabilization a theoretical study of angular motions of a spinning body has been completed. The purpose of this study was to obtain simple analytical expressions which describe the angular motions of a spin-stabilized body in space, both during application of a body-fixed perturbing moment and subsequent to termination of the moment. The analysis assumed a constant spin rate and small angles with roll rate about a space axis taken equal to roll about the body axis. Expressions for the motions were obtained and found to be in good agreement with digital solutions of Euler's dynamical equations.

Also in this area of spin stabilization, the magnetic effects of the earth's field on a spinning body are being considered. An expression for the precessional effect when the field is inclined to the spin axis has been derived for the case of an electrically-conducting cylinder. A calculation indicates that the time for the spin axis of a satellite to precess, say 10 degrees, in the direction of the field is fairly long, of the order of several months.

For those satellite missions wherein an orientation toward the center of the earth may be required, a program is being considered to investigate attitude sensors. For coarse sensing it appears possible and simpler to look through the atmospheric window at about 12 microns. Radiation measurements at satellite altitude are needed to show feasibility of this approach. The more complicated method of horizon detection by the earth-space radiation discontinuity is capable of better resolution. In this case it is the horizon of the troposphere that is detected. To avoid solar interference, radiation below several microns is filtered out. There are several ways that a scanner can be designed to do this job. Either one, two or several infrared radiation sensors and several possible modes of scanning action might be used. The scanner unit is mechanically simple for a single sensor but the associated electronics circuits needed to process the signal become more complex. The stability of the electrical circuit becomes an important consideration. A scanning action suitable to one satellite configuration may be unsuited to another which may partially block the field of view and reduce acquisition capability. The signal-to-noise ratio required for acceptable resolution is a factor of uncertainty and needs to be established by simulation and flight testing. Optics are required for a thermistor bolometer unit to concentrate radiation on the thermistor flake and to permit a narrow beam width of about 1 degree for satisfactory resolution. The response time and size of the flake enter into the permissable scanning rate and the beam width required for sufficient intensity of radiation. The advantages of the thermistor detector over a photoconductor type are constant sensitivity over the wavelength spectrum and the fact that cooling is not required. However, a gold-doped germanium photoconductor may also be competitive for missions of short duration. It is reported to be very sensitive out to 10 microns when operated at liquid nitrogen temperature.

Several studies on inertial reaction controls are being considered. One is an analog study to define the effects of servo-motor characteristics on a flywheel response to initial error. This is initially a one-degree of freedom study with no damping. The characteristics of available motors will be described and considered as the major variable.

In another study the transfer functions for several types of inertial controls are being determined as a first step in analysis of a control system for earth or solar orientation. The various types are a single gyro, two gyros, twin gyros and flywheels. The most critical condition for the single gyro is the condition of residual angular momentum of the satellite. Relative angular displacements between gyro and body will become large so that the directions of gyro control will be incorrect. However, if the residual angular momentum is closely zero, the single gyro can control two degrees of freedom at very little weight and at very low gyro rotational speed. This control may be better suited to star-tracking. The two-gyro control with single-degree gimbals should provide control with little cross coupling and permit small residual angular momentum. The twin gyro control with contra-rotating wheels to produce a single torque reaction on the vehicle results in no cross coupling at small angles. A disadvantage is that the twin gyros should rotate at the same speed but they are not mechanically connected. For these gyro controls the gyro speed can be varied as needed but this introduces additional complexity. The principal advantage of flywheel controls is in their simplicity. However, a large cross-coupling can occur between the flywheels and the wheels may attain their limiting speed in absorbing residual angular momentum. This is particularly true for earth orientation where constant torque would be needed to precess any residual angular momentum vector that is not perpendicular to the plane of the orbit. Clearly some additional means must be provided to remove any residual angular momentum and to unload the gyro or flywheel controls.

The problem of how to compensate to improve the control system response to command inputs while simultaneously accounting for disturbances or noise that may appear elsewhere in the system is being investigated by analytical and analog methods. Several compensation techniques are being formulated. One such technique would include a dynamic analogue of what the actual system should be doing. This would be compared with what the system is doing. The difference between the two is then made, the input to the compensation unit which must provide a "Make Up" input to the basic control system. This in effect is a simple form of adaptive control system.

SIMULATION

Several current simulation tests will next be described. Apparatus is being designed for testing the response of a horizon scan unit. Since the response depends on the net exchange of radiation to and from the thermistor flake and the thermistor has constant sensitivity with different wavelength, the simulation of the horizon can be made by provision of a "hot jump" discontinuity rather than a cold jump in which the 4° Kelvin temperature of space should be approximated. Experience with a small black body cavity unit as radiation source is expected to clarify this point.

Work is progressing on frictionless suspension systems using electro-magnetic suspension and air bearings to achieve 1 and 3-degrees of freedom. A large hemispherical air bearing has been completed for full-scale inertial simulation tests of the Mercury capsule.

Simple methods for despinning a satellite are under investigation. Initially, the method of unwinding and releasing small weights as proposed by JPL and tried on a Lunar prcbe will be simulated in a vacuum chamber. Apparatus is being made for this purpose. This method, as you may recall, works independently of the initial spin rate as long as the proper relation is held between the vehicle inertia, circumference, mass of the small weights and length of unwinding cable.

The effects of a magnetic field on spinning bodies is being explored. The purpose of this investigation is really twofold. First it is desired to simulate a spinning satellite acted upon by the magnetic field of the earth, to observe the damping of the spin and precession of the spin axis. Second, the possibility of "unloading" a flywheel control by directly utilizing the earth's magnetic field is also a consideration. Simple model support and spin-up apparatus have been set up inside a bell jar which is itself enclosed by a cylindrical electro-magnetic coil. The reason for this coil is to provide a significant magnetic damping effect in a relatively short time and to permit the use of ball bearings for support of the model spin axis. Admittedly these bearings do not permit as good a simulation as we would like for the satellite case since much higher initial spin rates are also required. Thus there is expected a larger interaction of the induced and principal magnetic fields which the simple theories neglect. Runs are being made with cylindrical models of different fineness ratio wall thickness and electrically-conducting material. Small air bearings have been designed to permit longer runs at lower field strength.

The dynamic behavior of flexible rotating structures is under investigation. This is one of several techniques being explored to erect large space structures. This project involves a study of the feasibility of using the centrifugal forces produced by rotation to give shape and rigidity to flexible, fabric-like structures. Experimental and analytical investigations have been conducted on two basic configurations; a flat disk and a paraboloid with a conical covering. Such shapes in space might serve as optical and/or radar reflectors, radio or radar antennas, or heat and light collectors.

Experiments with 3'- diameter models in a vacuum chamber have shown that not only are the centrifugal forces sufficient to sustain the required shapes, but that the small distortions, produced by gyroscopic forces when the direction of the axis of rotation is changed, quickly tend to damp out. This last result is an extremely important one inasmuch as the ability to orient the axis is a prime requisite for earth or sun seeking devices.¶ A mockup of a combination flywheel and bar magnet control system has been made. The system is floated in a water tank for "frictionless" support. A purpose of the dual control is to permit "unloading" of the flywheel at saturation speed by the bar magnet control which reacts against the earth's magnetic field. The flywheel control loop is considered to be the primary circuit which normally supplies 75 percent of the total control moment. The attitude error signal is presently derived from a C-2 compass gyro. It is planned to replace this by a light source and photoelectric cells and to try for a control accuracy of 1 second of arc. To determine this resolution accuracy, measurements of the flywheel motion will be made and adjusted by the known inertia ratio of flywheel to platform. Some analysis of the system is also being made. However, the simulator approach is proving to be a very rapid method of investigation.

A study of a man maneuvering in space is underway. The purpose of this investigation is to study how a man can motivate between two points in space using jet thrust. A simulator has been constructed that permits frictionless motion with one linear degree of freedom and one angular degree of freedom. A man is suspended by a cable, 38 feet below a wheel that runs on a rail. Any fore or aft angular deviation from the plumb bob direction is detected by an operator who controls the motion of the wheel to maintain plumb alinement of the cable. The "space man" is provided with air jets of about 9 pounds, maximum thrust. Two control arrangements have been tried. First the man was seated on a swing and given air jets which he held. With this setup a major problem was to control spin due to thrust misalignment. In this rig, experienced pilots performed better than engineers and after some experience even engineers became conditioned. The second rig consisted of 2 air jets, one front and one aft that were strapped onto the man. Foreward motion was obtained by pushing forward on a lever and visa versa. To produce a torque, the jets are swiveled by a linkage to the man's helmet. By squeezing the control stick with his head turned, both jets are then activated to produce a couple. With this setup yaw control was improved. Hand-held weights were also tried for yaw control. The tests have served very well to show the maneuver problem.

1. Reaction control apparatus

2. Rotation using head control

3. Rotation using inertia wheel effect

4. Traverse using Head Control

5. Traverse using variation of C. G. control

(A short movie will now be shown.)

SPACE FLIGHT EXPERIMENTS

We will conclude this presentation with brief remarks on space flight experiments. With regard to vertical probes, a 12-foot diameter Alumimum-Mylar sphere was successfully ejected and inflated at an altitude of 77 miles from a spin-stabilized 2-stage rocket vehicle. This was in preparation for a satellite launching.

The spin-up of a spinning rocket motor during the burning process due to internal swirling of exhaust gases has been measured from flight tests of two 10-inch spherical rocket motors. A 20 percent increase in spin rate was determined. A theoretical method of computing "spin-up" will be used to extend these results to larger motors of similar shape.

A ballistic probe is being developed for the purpose of testing several radiation-sensing devices with a view toward providing a suitable attitude control signal representative of the earth horizon or edge in relation to the sky background.

PROGRAM AREAS OF RESEARCH ON ORIENTATION IN SPACE

LANGLEY - FEBRUARY 1959

SURVEYS AND COMPARISONS

REQUIREMENTS AND TRADEOFFS

CONTROL SYSTEMS

SIMULATION TESTS

SPACE FLIGHT EXPERIMENTS

NASA L-1278-1 GILLESPIE 2/25-27/59

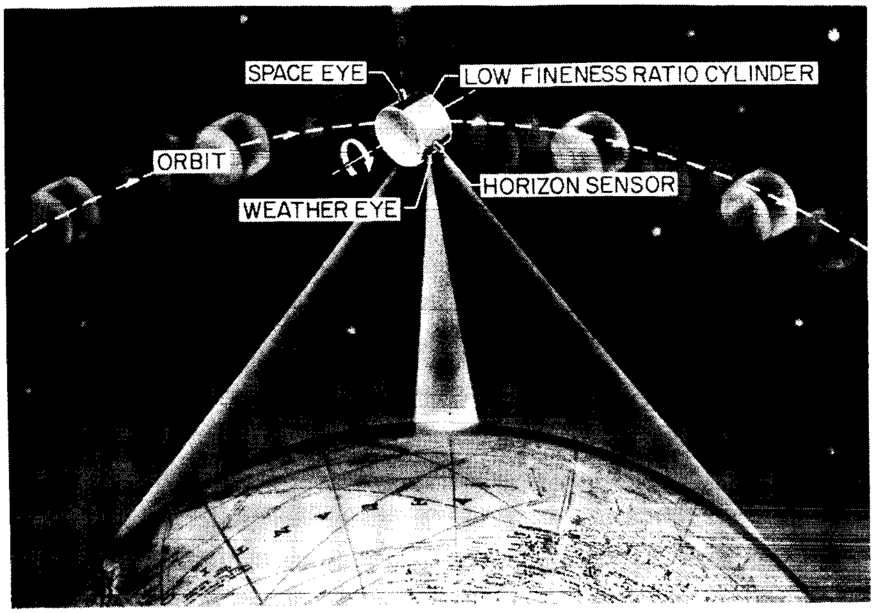
SURVEYS AND COMPARISONS

ATTITUDE CONTROL OF CIVILIAN EARTH SATELLITE VEHICLES

WEIGHT COMPARISON OF SEVERAL ATTITUDE CONTROLS FOR SATELLITES

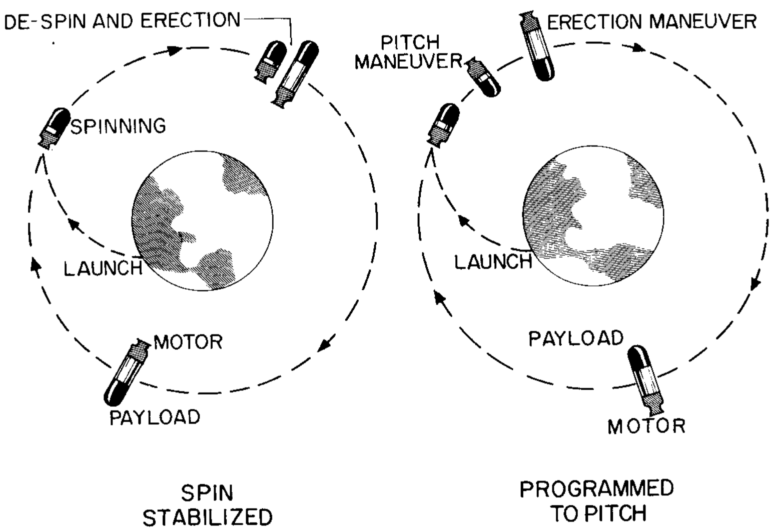
NASA L-1278-2 GILLESPIE 2/25-27/59

USE OF SPIN IN COMBINATION WITH AN HORIZON SENSOR



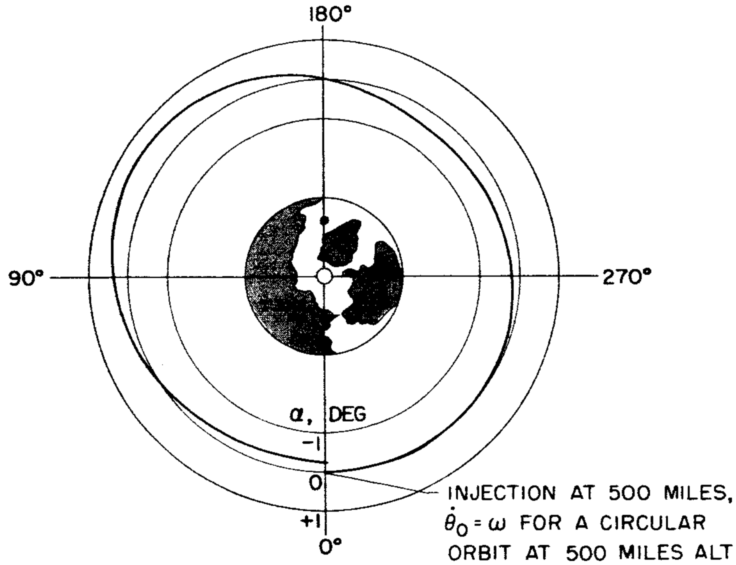
NASA L-1278-3 GILLESPIE 2/25-27/59

TWO LAUNCHING SCHEMES
FOR SATELLITES STABILIZED BY GRAVITATIONAL GRADIENT



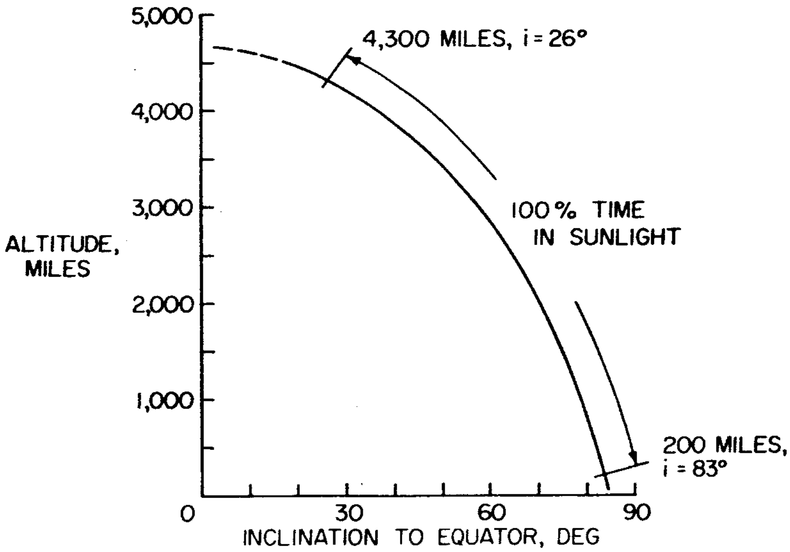
NASA L-1278-4 GILLESPIE 2/25-27/59

EFFECT OF AN ECCENTRIC ORBIT (e = 0.005) ON ATTITUDE TOWARD EARTH, GRAVITY METHOD



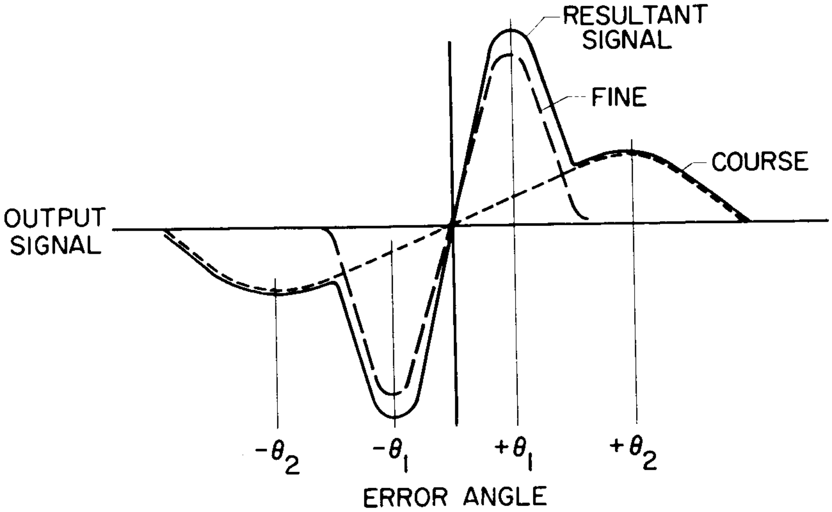
NASA L-1278-5 GILLESPIE 2/25-27/59

CIRCULAR ORBITS THAT PERMIT A CONTINUOUS VIEW OF THE SUN



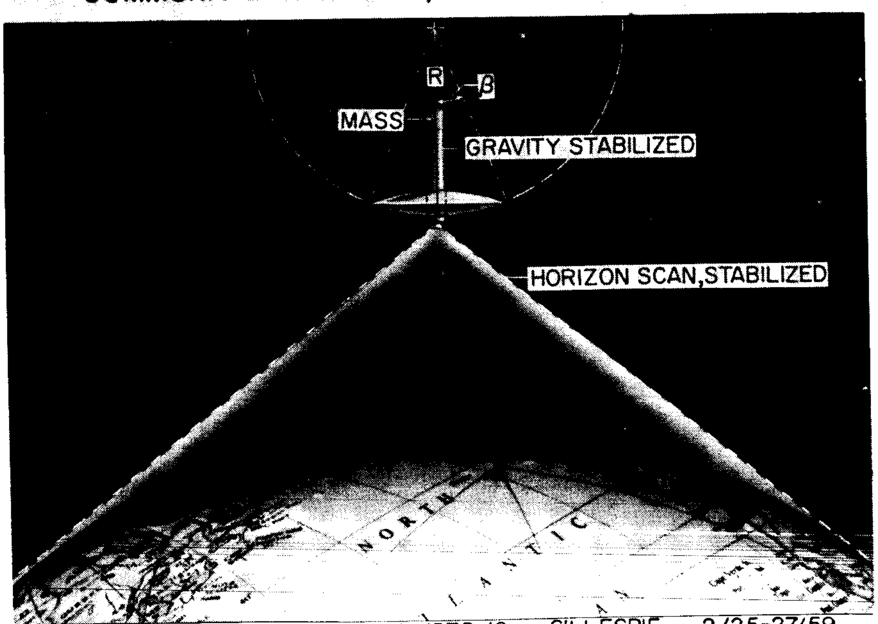
NASA L-1278-6 GILLESPIE 2/25-27/59

UNIVERSITY OF COLORADO ATTITUDE SIGNAL, SOLAR ORIENTATION



NASA L-1278-7 GILLESPIE 2/25-27/59

COMMUNICATIONS RELAY, PASSIVE-TYPE, STABILIZED



NASA L-1278-10 GILLESPIE 2/25-27/59

SOLAR-AND-EARTH ORIENTED

NASA L-1278-11 GILLESPIE 2/25-27/59

SIMULATION TESTS

ATTITUDE SENSING UNITS
CONTROLS
COMPLETE SYSTEM

CONTROL SYSTEMS

TYPES
ATTITUDE SENSORS
CONTROLS
SYSTEM ANALYSIS

SPACE FLIGHT EXPERIMENT

VERTICAL PROBES
SATELLITES

NASA L-1278-12 GILLESPIE 2/25-27/59